Drift of Sea Ice and Icebergs on the Labrador Shelf in 2009 and 2011 from Satellite-Tracked Ice Beacons

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DRIFT OF SEA ICE AND ICEBERGS ON THE LABRADOR SHELF

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ABSTRACT

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Sixteen satellite-tracked ice beacons were deployed on icebergs (or ice island fragments) and ice floes on the Labrador Shelf in March 2009 and 2011. The beacons reported data for longer periods in 2009 when the pack ice was thicker and more extensive, than in 2011. Maximum hourly ice speeds of over 1 m/s were observed in the offshore branch of the Labrador Current and off the southern Labrador coast in 2009, and on the nearshore Labrador Shelf in 2011 during strong northwesterly wind events. Iceberg velocities were also affected by spatially variable currents such as an eddy over Funk Island Bank in 2009. Two large tabular icebergs grounded on Nain Bank and the inner Labrador Shelf in 2009 became mobile during a strong northwesterly wind event when the ice edge moved shoreward, consistent with an increase in sea ice convergence and internal ice stress. In a regression analysis of iceberg and ice floe drift, surface wind accounted for 16-67% of the variability in the ice and iceberg alongshore and cross-shore velocity components.

RÉSUMÉ

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Seize balises de glace suivies par satellite ont été déployées sur des icebergs (ou des fragments d'île de glace) et des floes sur le plateau du Labrador en mars 2009 et 2011. Les balises ont fourni des données pendant des périodes plus longues en 2009, car la banquise était plus épaisse et plus étendue qu'en 2011. Des vitesses horaires maximales des glaces de 1 m/s ont été observées dans la section extracôtière du courant du Labrador et au large de la côte sud du Labrador en 2009, et dans la zone côtière du plateau du Labrador en 2011 pendant des épisodes de vent nord-ouest violent. Les vitesses des icebergs ont également été touchées par des courants variables dans l'espace, tels qu'un tourbillon au-dessus du banc de l'île Funk en 2009. Deux gros icebergs tabulaires se sont échoués sur le banc Nain et l'intérieur du plateau du Labrador est devenu mobile en 2009 pendant un épisode de vent nord-ouest violent alors que la lisière des glaces se déplaçait vers la côte, ce qui correspondait à une augmentation de la convergence des glaces de mer et des contraintes glacielles internes. Dans une analyse de régression de la dérive des icebergs et des floes, le vent de surface représentait 16 à 67 % de la variabilité des vitesses des glaces et des icebergs le long de la côte et sur le littoral transversal.

1.0. INTRODUCTION

During ice surveys conducted on the Labrador Shelf in March 2009 (Prinsenberg et al., 2011) and 2011 (Prinsenberg et al., 2012), satellite-tracked ice beacons were deployed on icebergs, ice island fragments and ice floes by helicopter. The ice beacons were deployed in collaboration with the Canadian Ice Service to provide drift data for testing iceberg and sea ice drift models, and for testing algorithms for identifying icebergs and ice island fragments in SAR imagery. This report provides further analysis of the data.

In addition to the ice beacons, helicopter-mounted sensors were also used to measure snow and first-year ice thickness along the flight paths. Mean ice thicknesses and the ice extent were much less in 2011 than in 2009 (Prinsenberg et al., 2013).

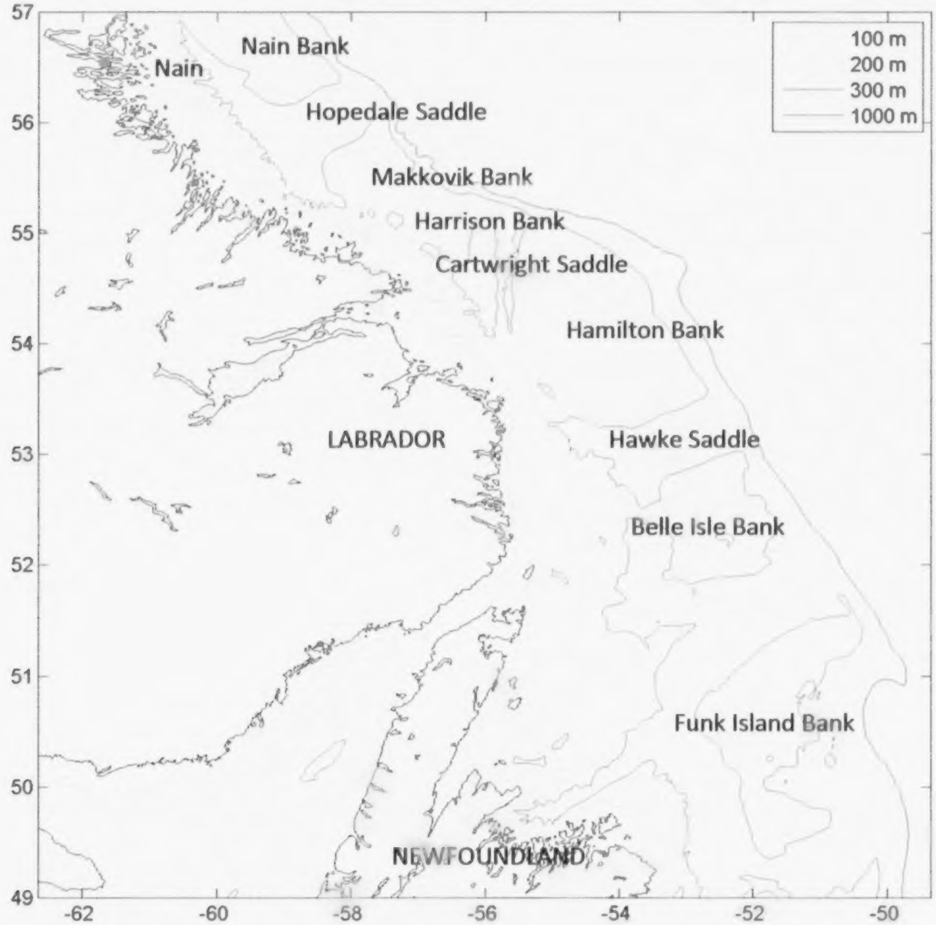

Fig. 1. Map of Labrador-Newfoundland Shelf.

2.0. MATERIALS AND METHODS

Each year, eight beacons were deployed by hand via helicopter. Four of these beacons were Iridium/GPS beacons designed and built at the Bedford Institute of Oceanography, the other four were ARGOS CALIB beacons manufactured by Metocean Data Systems Ltd. and provided by the Canadian Ice Service. Four of the beacons were deployed on icebergs and four were deployed on ice floes. The deployment times and locations for the ice beacons in 2009 and 2011 are listed in Tables 1 and 2, respectively. Photographs of the icebergs in 2009 and 2011 are shown in Figures 1 and 2, respectively.

The accuracy of ARGOS beacons is generally better than 500 m (based on Class 2 locations) (http://www.argos-system.org/web/en/78-faq.php#faq-264). The accuracy of the GPS beacons was 3 m (CEP=circular error probable) according to specifications, however the beacons deployed in 2009 appeared to be less accurate than those deployed in 2011. The GPS beacons provided hourly positions, while the ARGOS beacons provided positions at irregular intervals (usually more than once every 1.5 hours, but with a gap of 2-4 hours once per day).

Hourly ice velocity components were computed from hourly-interpolated positions. ARGOS positions were smoothed with a 5-point moving average filter to compensate for the lower accuracy of the measurements. The GPS positions in 2009 were de-spiked using differences from the median-filtered latitudes and longitudes.

Table 1. Ice beacons deployed in 2009.

ID number	I=Iridium, A=ARGOS Iceberg Dimensions	Start time (MM/DD/YYYY HH)	Start Lat Long	End time (MM/DD/YYYY HH)	End Lat Long
2519990	I, 7 m H Low Tabular	03/20/2009 20	56.418 -59.538	06/10/2009 16	54.532 -56.768
2611490	I Ice Floe	03/20/2009 14	55.401 -58.050	04/10/2009 16	54.224 -55.719
2611510	I Ice Floe	03/20/2009 14	55.598 -57.896	05/04/2009 17	51.007 -53.524
2616000	I, 90m H x 110m L High Tabular	03/20/2009 20	56.482 -59.503	06/17/2009 13	52.689 -55.708
44652	A, 12m H Small Wedge-shaped	03/20/2009 20	56.241 -59.690	05/17/2009 21	51.206 -51.731
44653	A Ice Floe	03/19/2009 14	55.530 -59.172	05/27/2009 14	50.940 -52.545
44656	A, 70m H x 110m L High Tabular	03/19/2009 19	55.850 -59.546	06/04/2009 14	54.400 -56.526
44658	A Ice Floe	03/19/2009 17	56.036 -59.132	05/16/2009 22	49.966 -52.533

Table 2. Ice beacons deployed in 2011.

ID number	I=Iridium, A=ARGOS Iceberg Dimensions	Start time (MM/DD/YYYY HH)	Start Lat Long	End time (MM/DD/YYYY HH)	End Lat Long
2483860	I Ice Floe	03/20/2011 20	55.308 -58.309	04/07/2011 19	52.644 -55.472
2483920	I, ~2.9m thick Ice Floe (MYI?)	03/20/2011 18	55.795 -58.684	03/21/2011 20	55.687 -57.797
2484860	I 4.5mH x 160mL x 145mW, Low Tabular or Ice Island Fragment	03/20/2011 13	55.315 -58.303	03/24/2011 03	54.739 -56.902
2489850	I 7mH x 90mL x 75mW, Low Tabular or Ice Island Fragment	03/20/2011 18	55.800 -58.705	03/24/2011 11	54.906 -57.383
44654	A Ice Floe	03/19/2011 21	56.054 -59.515	03/24/2011 11	55.987 -57.870
44655	A 19mH x 100mL x 100mW, Drydock	03/19/2011 22	56.050 -59.519	03/24/2011 02	55.198 -57.985
44656	A 5.3mH x 200mL x 100mW, Low Tabular or Ice Island Fragment	03/19/2011 20	56.244 -59.802	03/24/2011 04	55.312 -58.006
44657	A Ice Floe	03/20/2011 05	56.097 -59.528	03/24/2011 13	55.000 -57.838

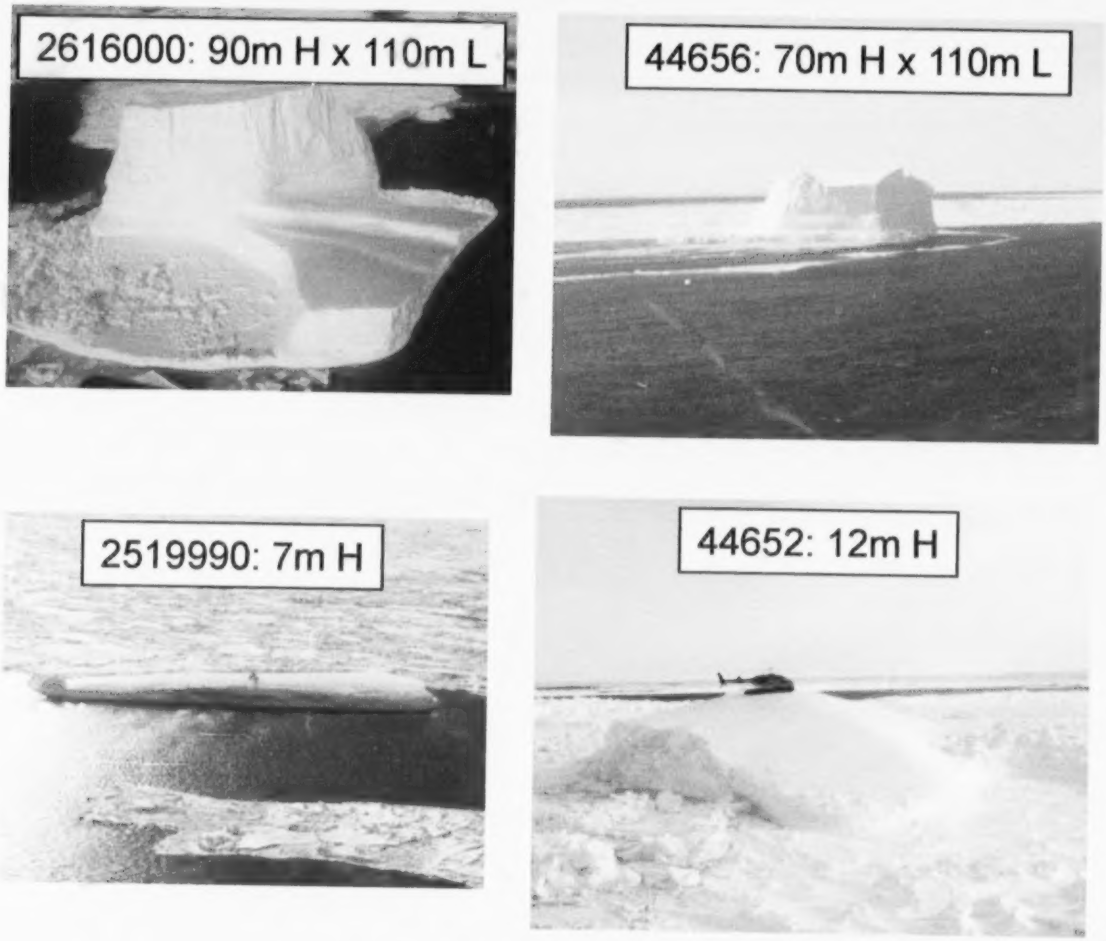

Fig. 1. Icebergs on which beacons were deployed in 2009. "H" indicates the estimated height and "L" the length.

44656: 200m x 100m, 5.3m high

44655: 100m x 100m, 19m high

2484860: 160m x 145m, 4.5m high

2489850: 90m x 75m, 7m high

Fig. 2. Icebergs or ice island fragments on which beacons were deployed in 2011.

3.0. ICEBERG AND ICE FLOE DRIFT SPEEDS

3.1. DRIFT IN 2009

The trajectories of the ice beacons deployed in 2009 are shown in Fig. 3. The hourly u (eastward) and v (northward) velocity components and speeds are shown in Fig. 4. The hourly velocity vectors are plotted in Fig. 5, along with the surface wind velocity (0.995 sigma level) at 55°N, 57.5°W, from the NCEP/NCAR Reanalysis dataset (Kalnay et al., 1996).

The two large tabular icebergs (2616000 and 44656) were grounded on Nain Bank and the inner Labrador shelf respectively, until day 105 (Fig. 3, 4) when there were strong northwesterly winds of close to 20 m/s (Fig. 5). They continued to drift southward with hourly drift speeds that never exceeded 1 m/s. Beacon 2616000 suddenly drifted westward toward the southern Labrador coast on day 150 when there were strong southeasterly winds (Fig. 5), and went aground. The trajectory of 44656 is overlaid on a RADARSAT-2 SAR image acquired on 22 April: day 112 (red line in Fig. 6). A band of consolidated ice can be seen along the coast north of Bulldog Is. It appears that the ice was compressed onshore, and then prevented from drifting south by the Island, and that iceberg 44656 was constrained to drift along the east side of the band of ice. It later went aground offshore of Hamilton Inlet.

The small tabular iceberg (2519990), the wedge-shaped iceberg (44652) and ice floe 44658 became entrained in the offshore branch of the Labrador Current where hourly drift speeds at times exceeded 1 m/s on day 80-87. Beacon 2519990 went aground off Cape Harrison on day 90. Hourly drift speeds for beacons 44652 and 44658 again exceeded 1 m/s on day 106 as they drifted southward along the southern Labrador coast. On day 126 when there were strong southerly winds, iceberg 44652 drifted eastward toward the northern flank of Funk Island Bank, where it then drifted in a clockwise loop. AMSR-E passive microwave images (Cavalieri et al., 2004) showing sea ice over the Labrador-Newfoundland Shelf indicate that an eddy was present in this location (Fig. 7).

Ice floe 44653 drifted slowly along the inner Labrador shelf north of Hamilton Inlet. However to the south, drift speeds exceeded 1 m/s on day 117 when there were strong northwesterly winds. Ice floe 2611510 also drifted along the inner Labrador shelf, with a maximum hourly speed of 0.9 m/s off the southern Labrador coast on day 108. Beacon 2611490 on an ice floe stopped transmitting regularly a few days after deployment.

The large tabular icebergs were grounded until day 105 (April 15) when there were strong northwesterly (alongshore) winds. Therefore they could have become mobile due to increased loads from wind stress, wind-driven currents, or internal sea-ice stress, or because of increased water level associated with wind-driven currents. In order to check

the last possibility, observed water level at Nain, NL was plotted in Fig. 8. Although there may have been some effect of wind on water levels on day 105, the maximum level was still less than it had been several days previously. On the other hand, a sequence of AMSR-E images from April 10 to 16 (Fig. 9) show that the ice edge moved shoreward between April 13 and April 16, suggesting that alongshore winds resulted in ice convergence on the Labrador Shelf. This would increase the internal ice stress on the grounded tabular icebergs (northernmost red dots), since internal ice stress is a function of ice concentration and thickness, both of which would increase due to ice convergence.

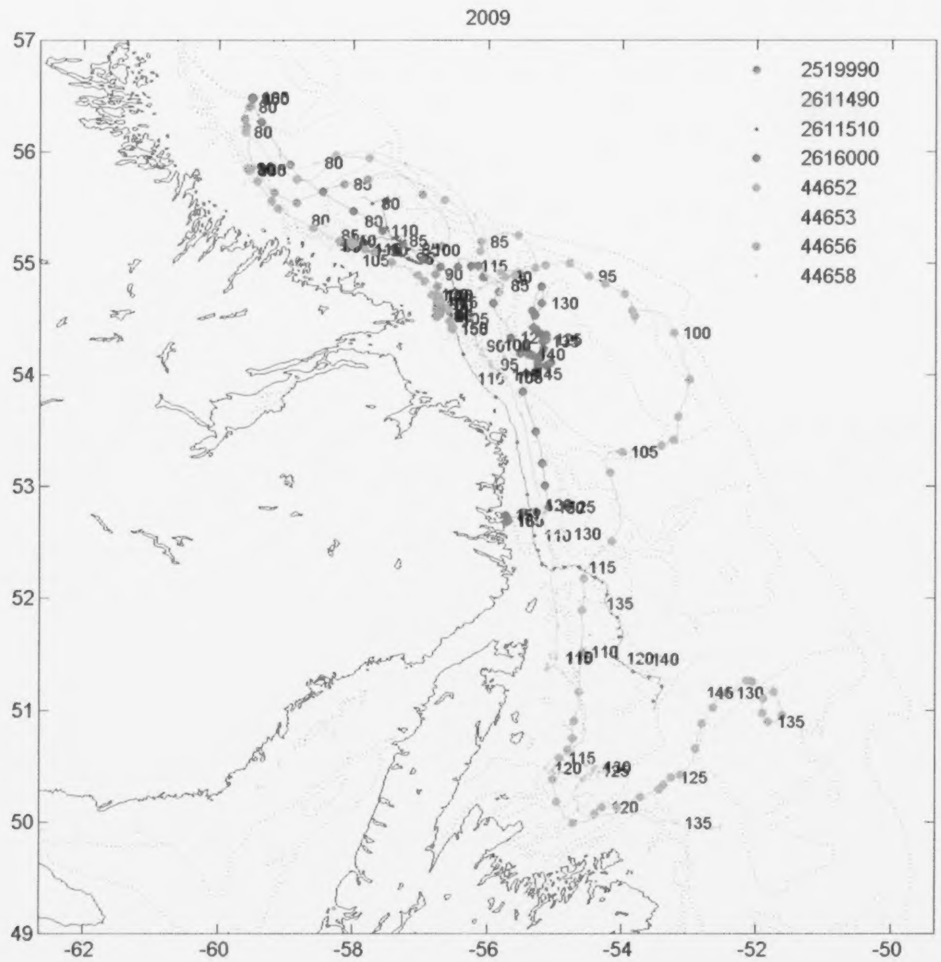

Fig. 3. Ice beacon trajectories in 2009. The positions are marked every day and labelled every 5 days with the day of the year.

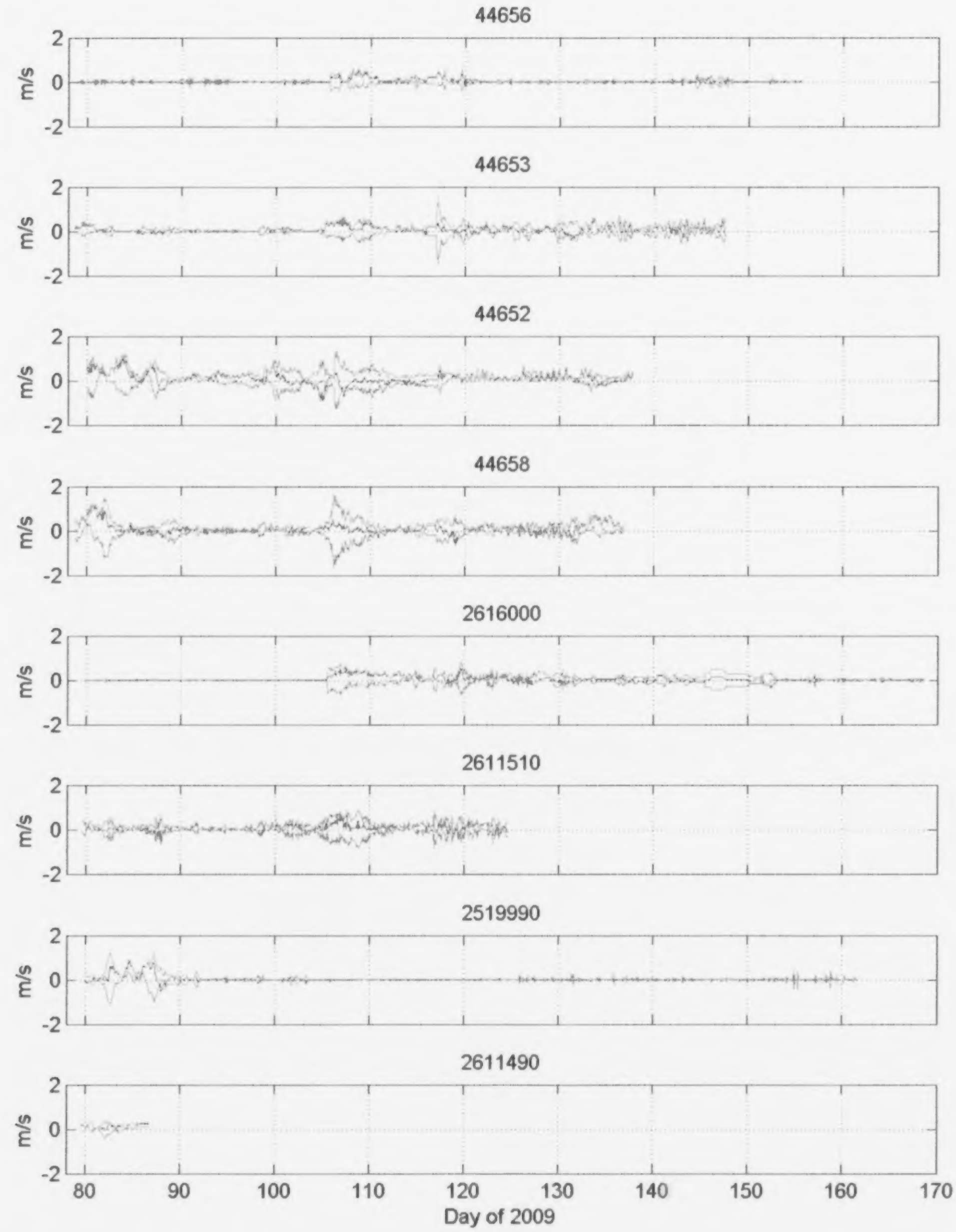

Fig. 4. Hourly u (eastward, blue) and v (northward, green) velocity components and drift speed (red) for beacons deployed in 2009.

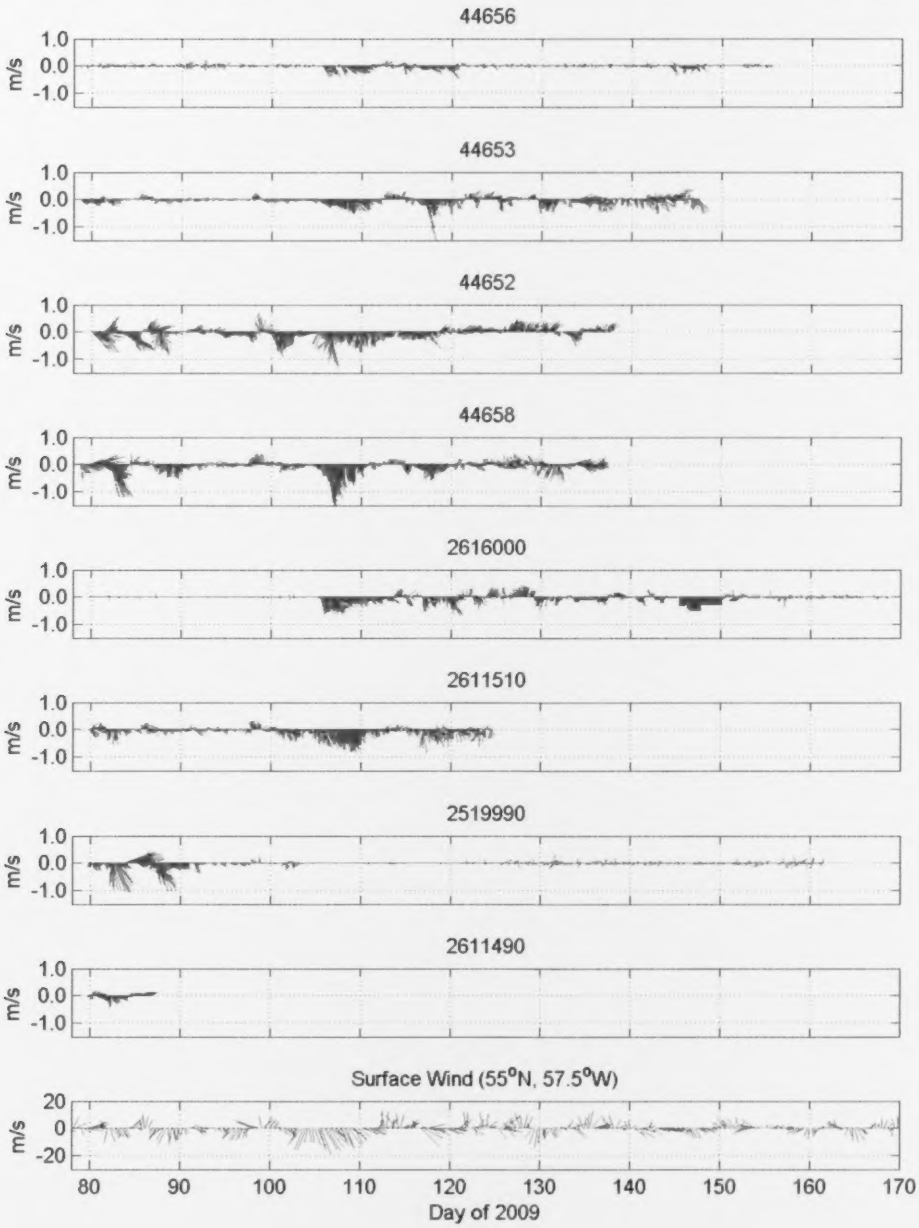

Fig. 5. Hourly ice velocity (top 8 panels) and surface wind at three grid points from the NCEP/NCAR reanalysis dataset (bottom 3 panels, continued on next page) in 2009.

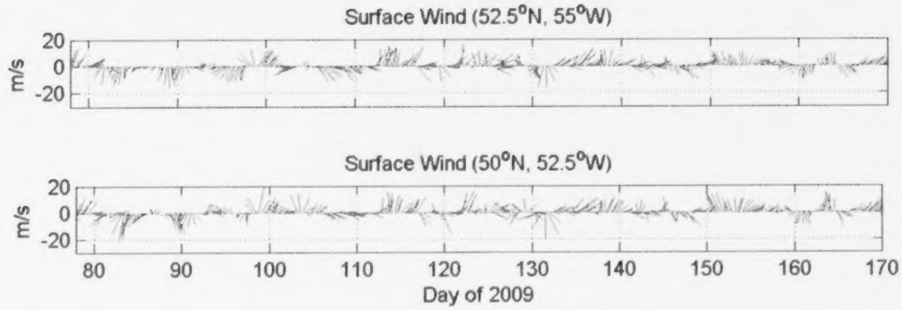

Fig. 5. (continued).

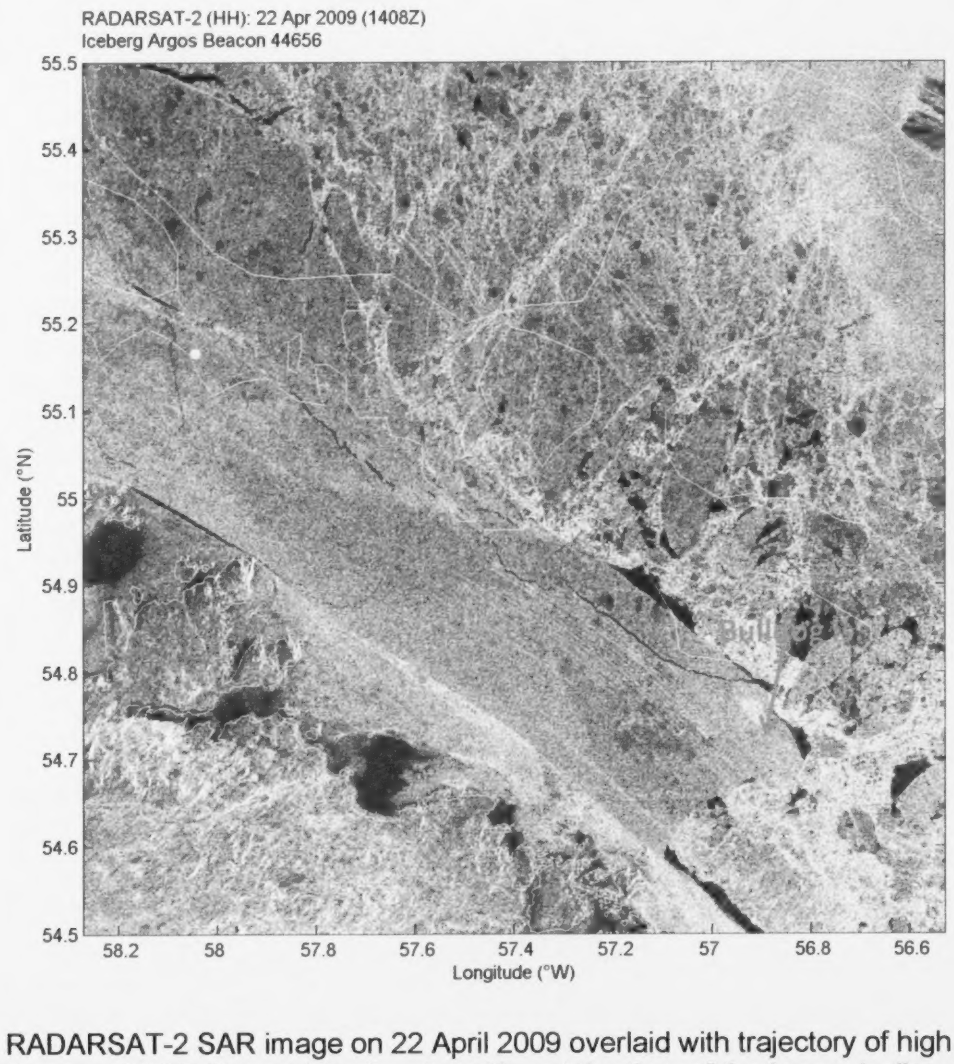

Fig. 6. RADARSAT-2 SAR image on 22 April 2009 overlaid with trajectory of high tabular iceberg 44656 (thin red line) and position at the time of the image (yellow dot). (RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2009) - All Rights Reserved).

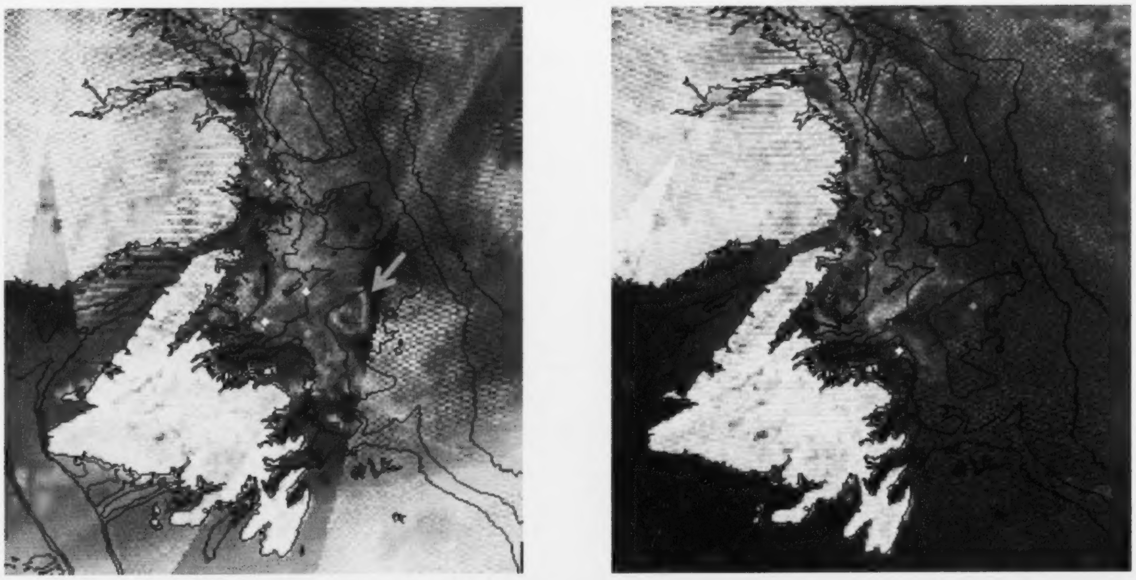

Fig. 7. AMSR-E passive microwave images (AE-SI6, Cavalieri et al., 2004) of Labrador-Newfoundland Shelf for 04 May (day 124, left) and 14 May (day 134, right), 2009, showing ice in eddy over Funk Island Bank (red arrow), and beacon 44652 (southernmost red dot).

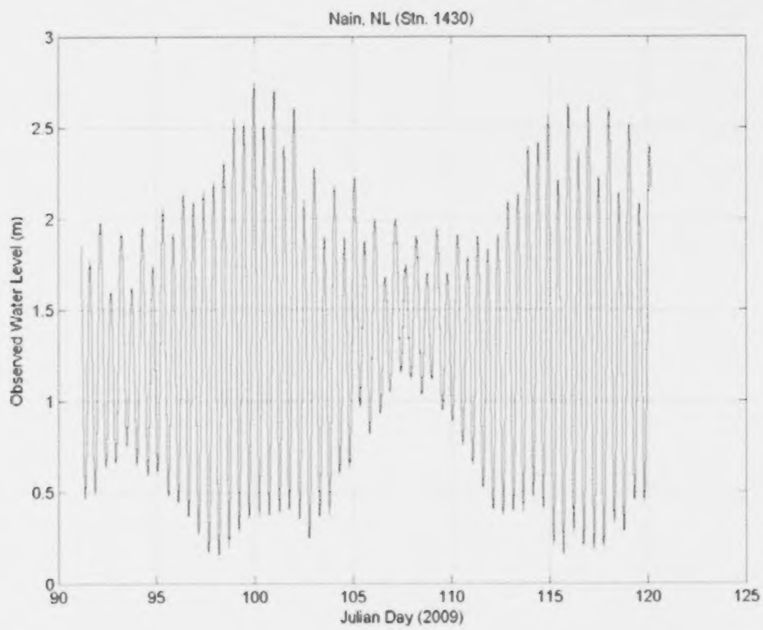

Fig. 8. Observed water level at Nain, NL (Station 1430).

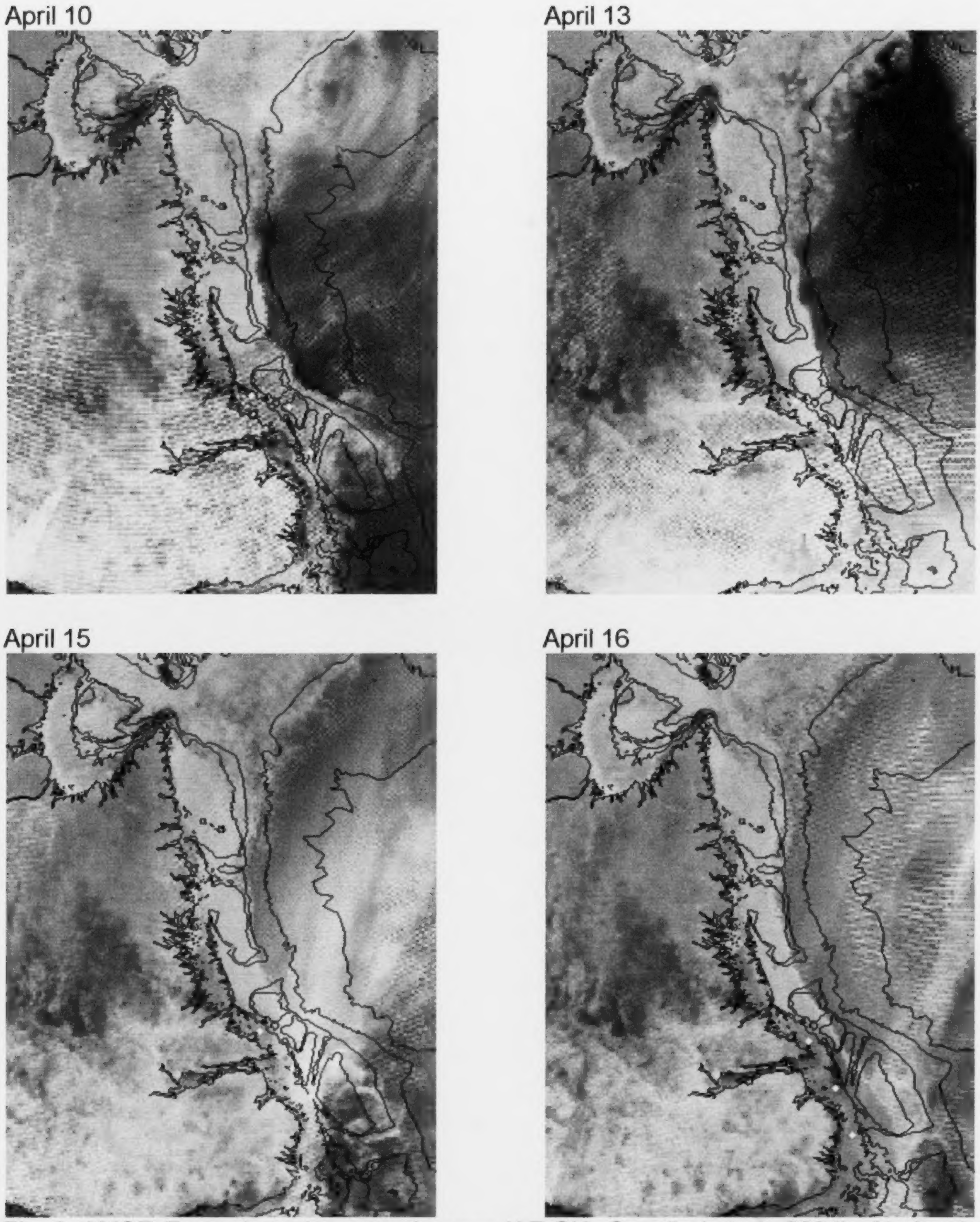

Fig. 9. AMSR-E passive microwave images (AE-SI6, Cavalieri et al., 2004) of Labrador Shelf on April 10, 13, 15, and 16, 2009 (days 100, 103, 105, 106). The beacon-tracked icebergs and floes are marked with red and blue dots respectively.

Figure 9 also shows that the drift of the wedge-shaped iceberg (easternmost red dot) clockwise around Hamilton Bank was consistent with the apparent drift of sea ice. On April 10, there is an ice tongue extending along the northeast side of the Bank, and on April 15, there is an eddy-like feature over the Bank.

3.2 DRIFT IN 2011

In 2011, the eight ice beacons were deployed in four pairs, with a beacon deployed on an iceberg and another beacon deployed on a nearby ice floe for each pair. The trajectories of the ice beacons are shown in Fig. 10. The hourly u (eastward) and v (northward) velocity components and speeds are shown in Fig. 11. The hourly velocity vectors are plotted in Fig. 12, along with the surface wind velocity at 55°N, 57.5°W, from the NCEP/NCAR Reanalysis dataset.

One of the ice floes (2483920) stopped transmitting within a day of deployment. It appeared to have been entrained in a current jet along the north side of Makkovik Bank, as winds were weak at the time (Fig. 9). Six of the eight beacons stopped transmitting on day 83, when there were north-northwesterly winds exceeding 15 m/s, during which the pack ice became compressed against the coast. The waves generated by this storm probably washed the beacons off the icebergs and ice floes; some of the beacons may have been lost due to ice rafting. The speeds of two of the icebergs (2484860 and 2489850) were ~0 m/s just before transmission stopped, suggesting that the icebergs became immobile as they became compressed against the shoreline, along with the surrounding pack ice. Beacon 2483860 on an ice floe continued to drift southward. Although it was close to iceberg 2484860 which became immobile, it was slightly farther south where it apparently avoided being trapped in the ice compressed against the shoreline. High drift speeds on days 94 and 97 were in agreement with strong northerly winds.

Figure 13 shows hourly speeds are shown in Fig. 13 for the iceberg/ice-floe pairs. A semi-diurnal tidal component is evident in the speeds, however the speeds are clearly noisier for the ARGOS beacons (upper two panels) than the Iridium/GPS beacons (lower two panels) because of the lower accuracy of ARGOS positioning. For iceberg 44656 (tabular) and floe 44657, speeds were higher for the floe than the iceberg, likely due to the greater influence of alongshore winds for the floe. A similar pattern is seen for iceberg 44655 (drydock) and floe 44654.

The speeds of iceberg 2484860 and floe 2483860 were very similar, likely due to the low height (and presumed low draft) of the iceberg. For iceberg 2489850 (decayed tabular) and floe 2483920, the speed of the floe was different than that of the iceberg or other beacons because the floe appeared to have been entrained in a current jet along

the north side of Makkovik Bank. Iceberg 2484860 could be detected in a Fine Quad-Pol RADARSAT-2 image acquired near the time of beacon deployment (Peterson et al., 2012).

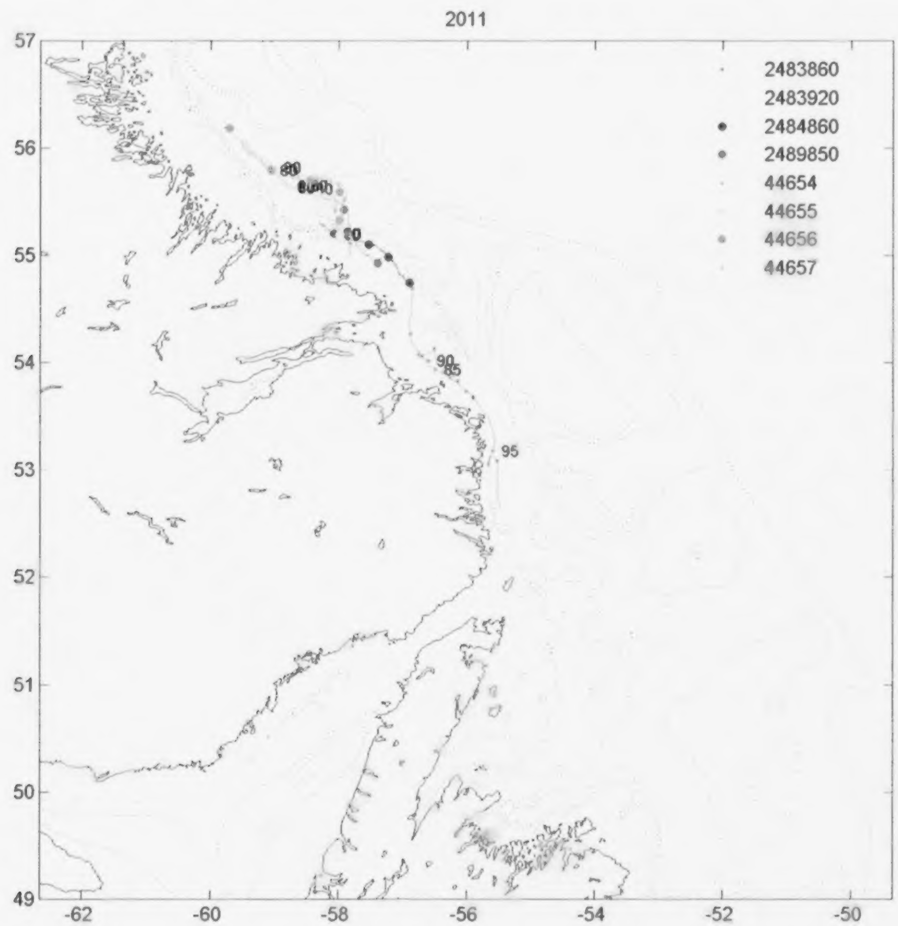

Fig. 10. Ice beacon trajectories in 2011. The positions are marked every day and labelled every 5 days with the day of the year.

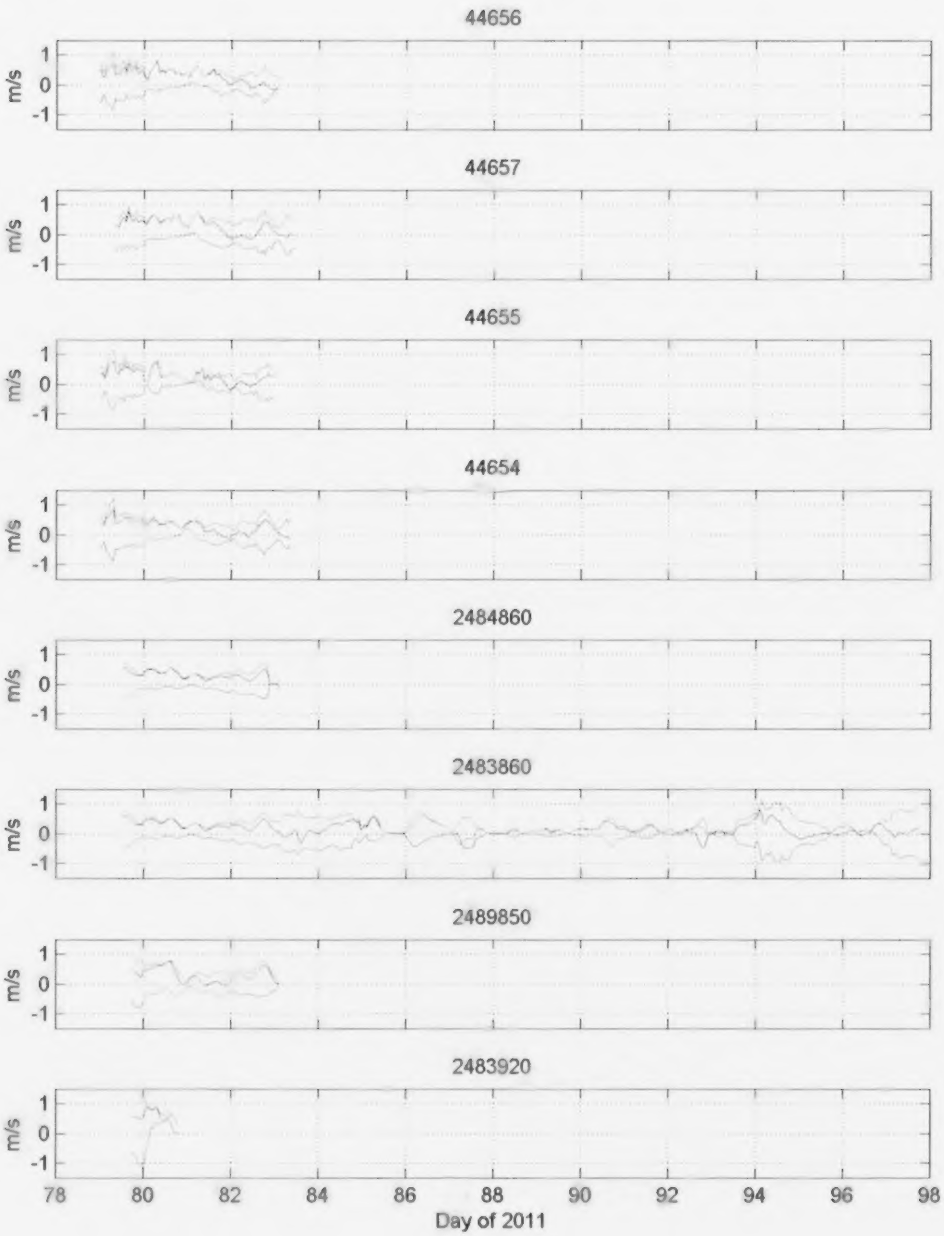

Fig. 11. Hourly u (eastward, blue) and v (northward, green) velocity components and drift speed (red) for beacons deployed in 2011.

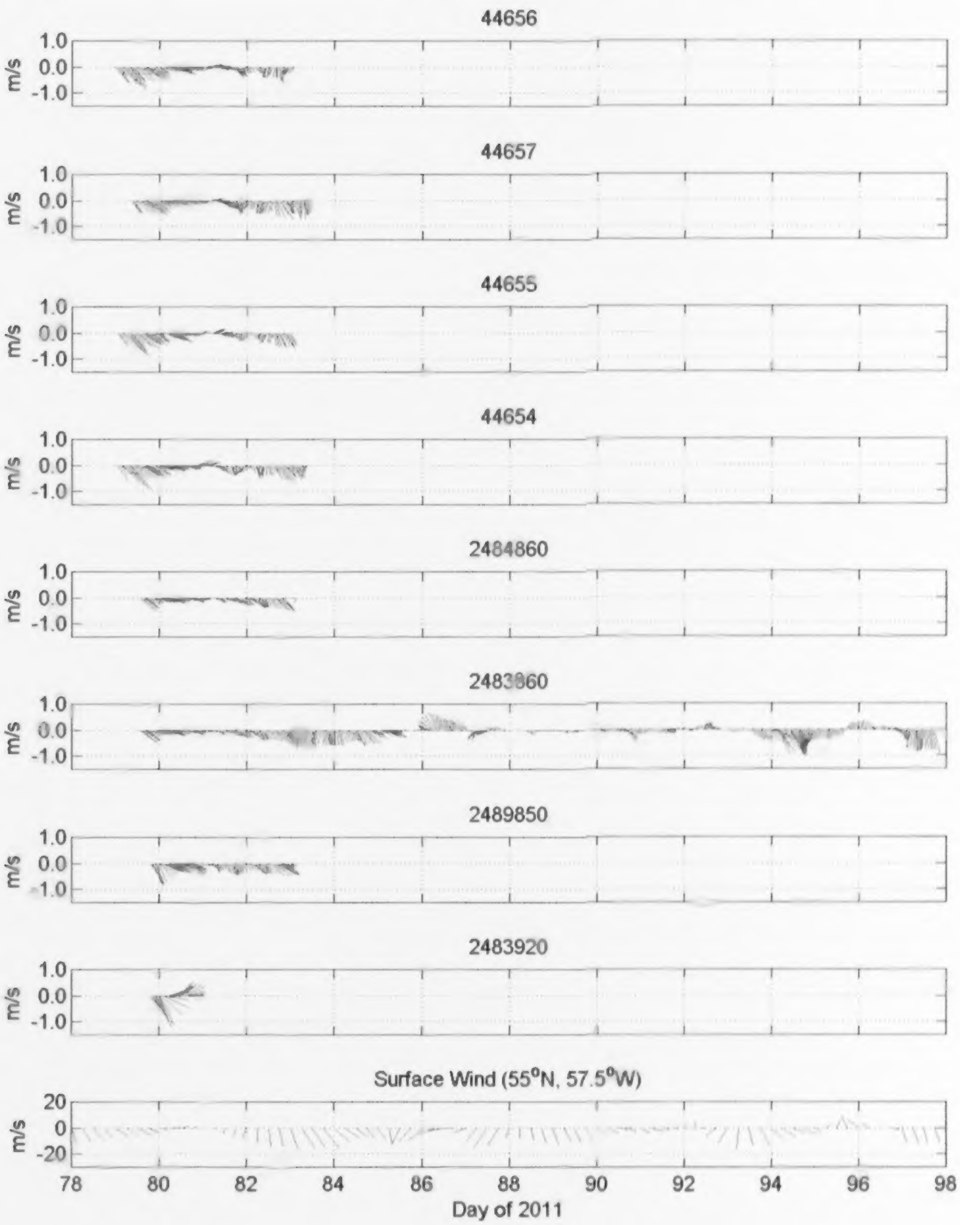

Fig. 12. Hourly ice velocity (top 8 panels) and surface wind at 55°N, 57°W from the NCEP/NCAR reanalysis dataset (bottom panel) in 2011.

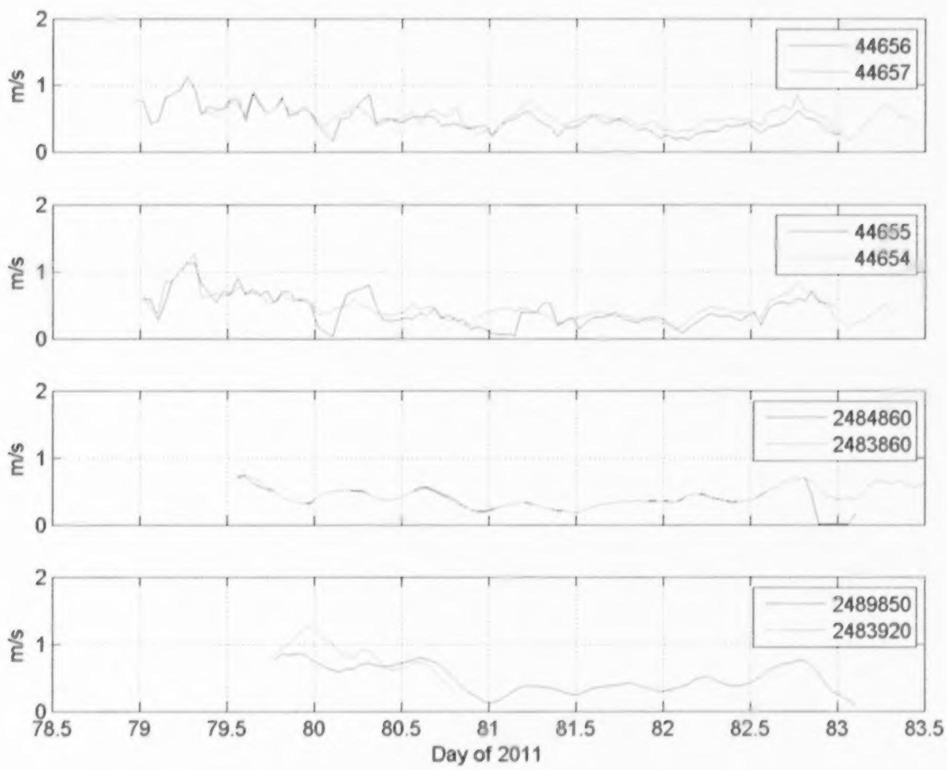

Fig. 13. Hourly ice speed for the four iceberg/ice-floe pairs deployed in 2011. Blue curves are iceberg tracks and red curves are ice floe tracks.

4.0 MEAN AND MAXIMUM ICE SPEEDS

The mean and maximum hourly speeds for the beacons deployed in 2009 and 2011 are shown in Tables 2 and 3 respectively. The maximum speeds for the ARGOS and GPS beacons were not noticeably different, despite lower accuracy and smoothing of the ARGOS beacon data.

In 2009, maximum hourly ice speeds of over 1 m/s were observed along the southern Labrador coast with beacons 44658 (ice floe) and 44652 (small wedge-shaped iceberg) on day 106 and with beacon 44653 (ice floe) on day 117 during strong northwesterly winds. They were also observed in the offshore branch of the Labrador Current with beacon 2519990 (low tabular iceberg) on day 87. Mean hourly speeds were generally 0.2-0.3 m/s, with speeds less than 0.15 m/s due to iceberg grounding.

In 2011, maximum hourly ice speeds of over 1 m/s were observed with beacons 44654 (ice floe), 44655 (drydock iceberg) and 44656 (low tabular iceberg) on day 79, with beacon 2483920 (ice floe) on day 80, and with beacon 2483860 (ice floe) on day 94.

Table 3. Mean and maximum hourly drift speeds of icebergs and ice floes in 2009.

ID number	Number of Days	Mean hourly speed (m/s)	Day of Max Speed	Maximum Hourly Speed (m/s)
2519990	81.7	0.08	87.3	1.21
2611490	7.1	0.21	82.2	0.40
2611510	45.0	0.23	108.8	0.89
2616000	88.7	0.13	119.6	0.85
44652	57.8	0.33	106.3	1.32
44653	68.8	0.19	117.1	1.51
44656	76.6	0.08	108.7	0.58
44658	58.0	0.29	106.2	1.73

Table 4. Mean and maximum hourly drift speeds of icebergs and ice floes in 2011.

ID number	Number of Days	Mean hourly speed (m/s)	Day of Max Speed	Maximum Hourly Speed (m/s)
2483860	18.2	0.35	94.2	1.15
2483920	1.0	0.81	80.0	1.27
2484860	3.5	0.37	79.6	0.73
2489850	3.3	0.49	79.9	0.86
44654	4.3	0.46	79.3	1.26
44655	4.0	0.43	79.3	1.12
44656	4.1	0.48	79.3	1.13
44657	4.1	0.51	79.6	0.93

5.0 ICE-WIND REGRESSION

A brief comparison of daily ice velocity components with surface wind at 55°N, 57.5°W was done using multiple regression analysis (Table 5). Only four beacons were used because of the shortness of many of the records, and because the icebergs were grounded for much of the time. The regression equation was

$$Y = B0 + B1 * U_w + B2 * V_w + \varepsilon,$$

where Y is U or V, the alongshore and cross-shore ice velocity components (with U in the downstream direction and V 90° to the left of U), U_w and V_w are the alongshore and cross-shore wind components, B0, B1, and B2 are constants, and ε is the error term.

The downstream direction was computed from the mean value of the velocity components. Data south of 52.5°N were not included.

In Table 5, the magnitude of (B1, B2) (i.e. $\mathrm{sqrt}(B1^2 + B2^2)$) is 2.9-3.8% of the wind speed for the alongshore component, U and 0.9-2.2% of the wind speed for the cross-shore component, V. Lower coefficients are expected for the cross-shore component than the alongshore component, especially nearshore, because of the coastal constraint. The signs of B1 and B2 are consistent with a drift direction to the right of the wind direction. The multiple correlation coefficient is 0.40-0.82, with higher coefficients in the alongshore direction, generally because of the coastal constraint in the cross-shore direction. Thus wind accounts for 16-67% of the variance in the ice velocity components. The constant term B0 is less than 0.10 m/s, except for the alongshore component for iceberg 44652 in 2009 (0.24 m/s). This higher value is due to the iceberg being in the offshore branch of the Labrador Current.

Much of the residual error is due to spatially variable currents and to internal ice stress. There is some error associated with spatially variable wind, although the wind vector plots in Fig. 5 show that the NCEP wind is very coherent between 55°N and 52.5°N. There is expected to be less error associated with other wind datasets having higher resolution, such as Environment Canada's Regional GEM (Global Environmental Multiscale) Model (http://weather.gc.ca/grib/grib2_reg_15km_e.html).

Table 5. Results of multiple regression analysis of daily iceberg and ice floe alongshore (U) and cross-shore (V) velocity components. The direction refers to the direction of the positive U component.

Year	Beacon	Days	Direction (°T)	Y	B0 (m/s)	B1	B2	R
2009	44652	80-106	139	U	0.24	0.012	0.028	0.60
				V	0.08	-0.019	0.010	0.55
	44653	80-129	156	U	0.06	0.027	0.010	0.64
				V	0.01	-0.010	0.007	0.42
	44658	80-106	147	U	0.07	0.034	0.014	0.64
				V	0.06	-0.012	0.016	0.61
2011	2483860	80-96	145	U	0.07	0.029	0.024	0.82
				V	0.06	-0.008	0.004	0.40

6.0 CONCLUSIONS

Sixteen satellite-tracked ice beacons were deployed on icebergs (or ice island fragments) and ice floes on the Labrador Shelf in March 2009 and 2011. The beacons lasted much longer in 2009 when the pack ice was thicker and more extensive, than in 2011.

In 2009, maximum hourly ice speeds of over 1 m/s were observed in the offshore branch of the Labrador Current and off the southern Labrador coast during strong northwesterly wind events. Iceberg velocities were also affected by spatially variable currents other than the Labrador Current, such as an eddy over Funk Island Bank. Two large tabular icebergs that were grounded on Nain Bank and the inner Labrador Shelf became mobile during a strong northwesterly wind event, during which the ice edge moved shoreward. This is consistent with an increase in sea ice convergence and internal ice stress.

In 2011, most of the beacons failed a few days after deployment during a strong north-northwesterly wind event when the pack ice became compressed against the coast. The speeds of ice floes near the icebergs were equal to or greater than the iceberg speeds, likely due to the greater influence of surface winds for the floes.

In a regression analysis of iceberg and ice floe drift, surface wind accounted for 16-67% of the variability in the ice and iceberg alongshore and cross-shore velocity components.

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